Supersymmetry, Dark Matter and Electroweak Baryogenesis

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Standard Model

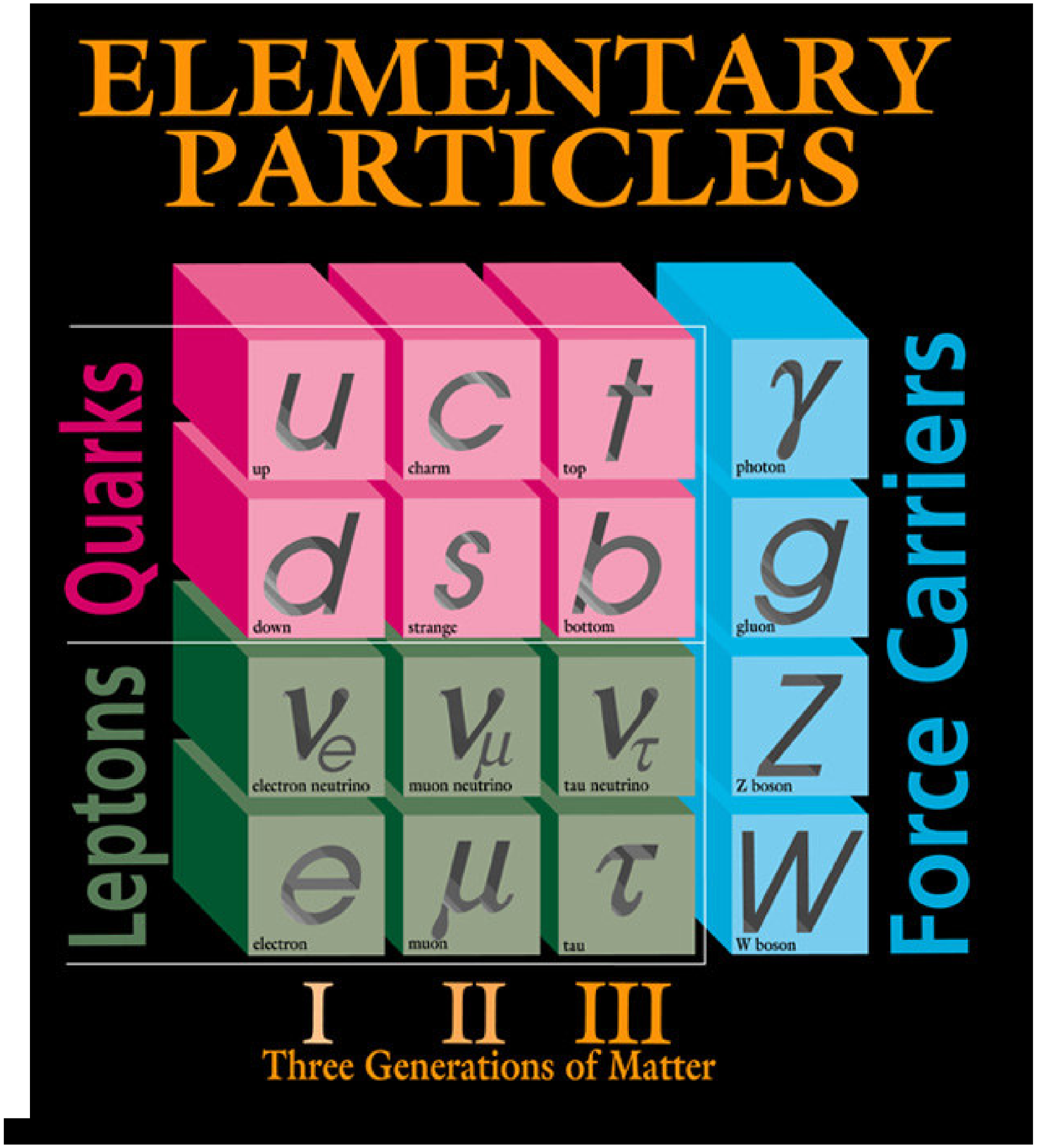
- Gauge Theory Based on the group

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

- All particle interactions of the three families of quarks, charged leptons and neutrinos well described by the Standard Model (SM)

- Excellent description of all experimental observables

- Includes heavy particles, like the top quark and the weak gauge bosons, as well as the almost massless neutrinos.



ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
γ
photon
d
down
s
strange
b
bottom
g
gluon
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson
I
II
III
Three Generations of Matter

Particles and Forces

Photons mediate standard electromagnetic interactions.

Quarks carry fractional charges.

Quarks form baryons (nucleons) and interact via strong forces mediated by gluons. They are confined inside hadrons.

Both quarks and leptons interact with the short range weak forces mediated by the heavy W and Z gauge bosons, with masses of order 100 GeV (1 GeV = Proton Mass).

Responsible for beta decay

$$\mathrm{n} \Rightarrow \mathrm{p} + \mathrm{e} + \bar{\nu}$$

Open questions in the Standard Model

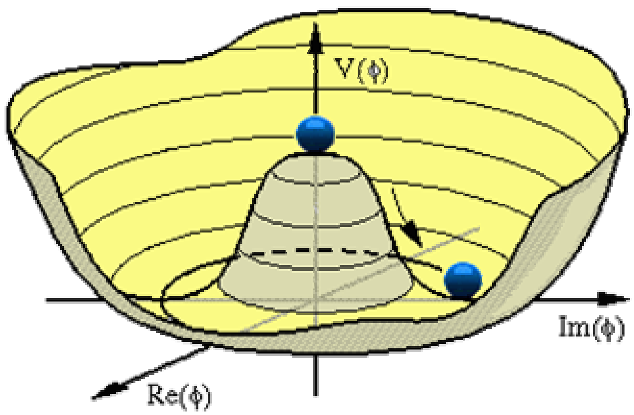
- Source of Mass of fundamental particles.

- Origin of the observed asymmetry between particles and antiparticles (Baryon Asymmetry).

- Nature of the Dark Matter, contributing to most of the matter energy of the Universe.

- Quantum Gravity and Unified Interactions.

The Higgs Mechanism



Masses of fermions and gauge bosons proportional to their couplings to the Higgs field:

$$M_{w,z} = g_{w,z}\ v$$

$$m_{top} = h_{top}\ v$$

$$m_H^2 = \lambda\ v^2$$

A scalar (Higgs) field is introduced. The Higgs field acquires a nonzero value to minimize its energy

Spontaneous Breakdown of the symmetry $< \phi > = v$

Vacuum becomes a source of energy = a source of mass

Spontaneous Symmetry Breaking

Vacuum expectation value may computed from effective potential

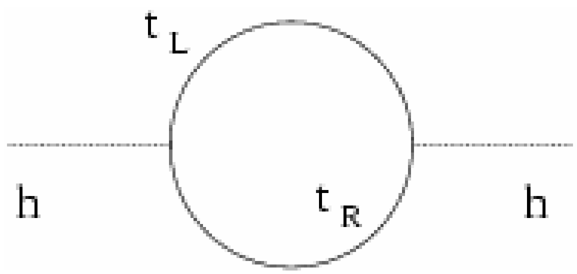
$$V(H) = m_H^2 \; H^2 + \lambda H^4$$

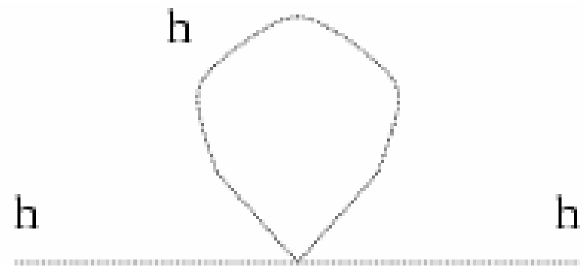
For negative values of the mass parameter

$$v^2 = -\frac{m_H^2}{2\lambda}$$

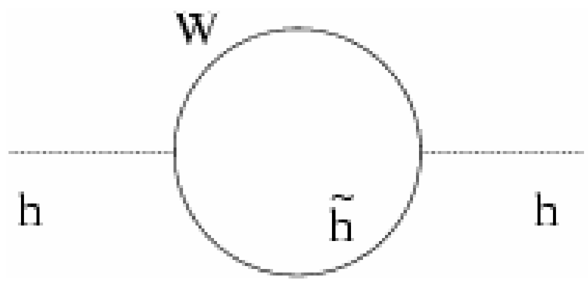
Problem: Mass parameter unstable under quantum corrections.

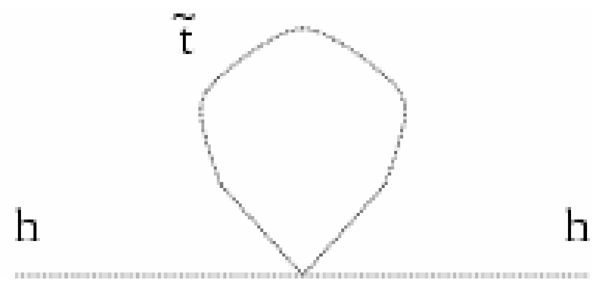
Quantum corrections induce quadratic divergent result





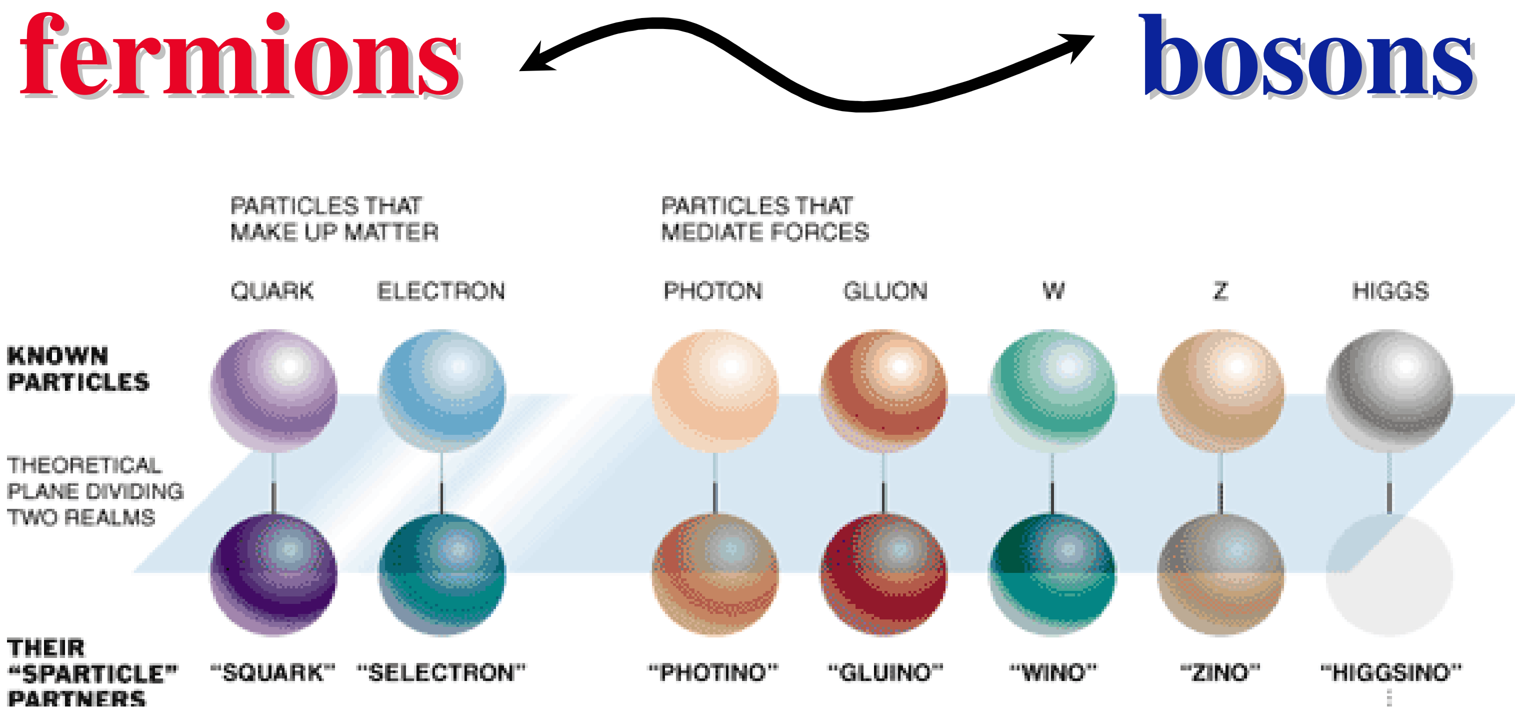
$$\delta m_H^2 \approx (-1)^{2S_i} \frac{n_i\, g_i^2}{16\pi^2} \Lambda^2$$





Cancelled if particles of different spin with same couplings are present. This happens naturally within a supersymmetric extension of the Standard Model

supersymmetry



Photino, Zino and Neutral Higgsino: Neutralinos

Charged Wino, charged Higgsino: Charginos

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)

Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy

- Supersymmetry algebra contains the generator of space-time translations.
Necessary ingredient of theory of quantum gravity.

- Minimal supersymmetric extension of the SM :
Leads to Unification of gauge couplings.

- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.

- If discrete symmetry, $P = (-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter.

Upper Bound on the Lightest Higgs Mass (minimal SUSY)

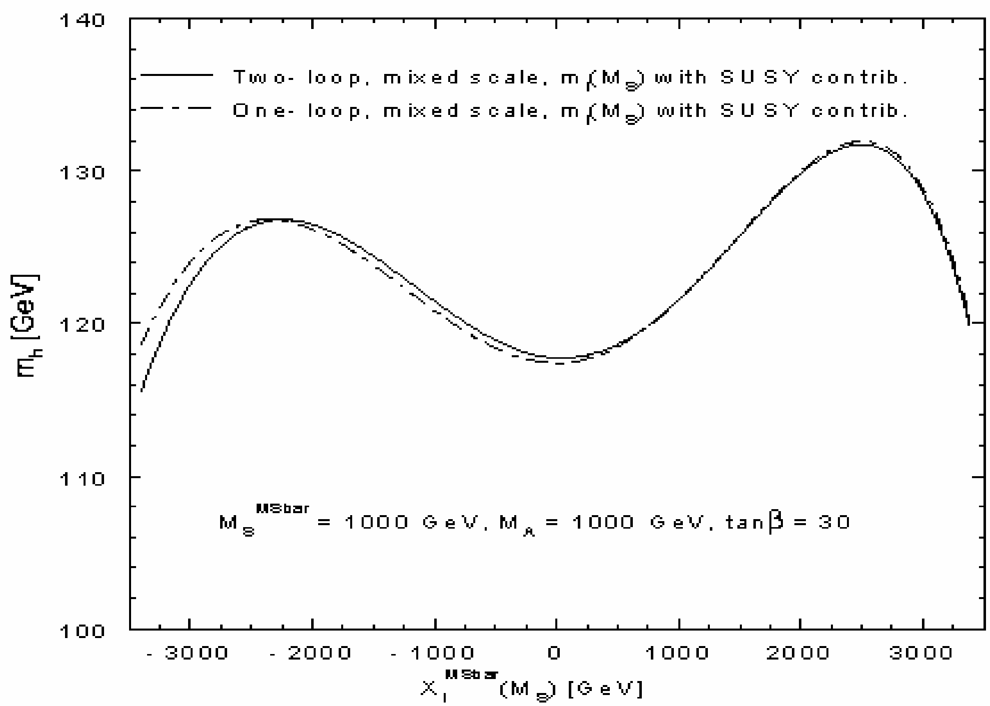
Supersymmetry requires two Higgs doublets. Two CP-even and one CP-odd neutral Higgs bosons.

$$< H_2 > = v_2 \quad , \quad < H_1 > = v_1$$

M_s= Mass of the top-quark superpartner

M_A = Mass of the heavy neutral Higgs bosons

X_t = Left-right Stop mixing parameter



Lightest Higgs boson mass smaller than 135 GeV.

M. Carena, M. Quiros, C.W. (1996); with Haber et al. (2000)

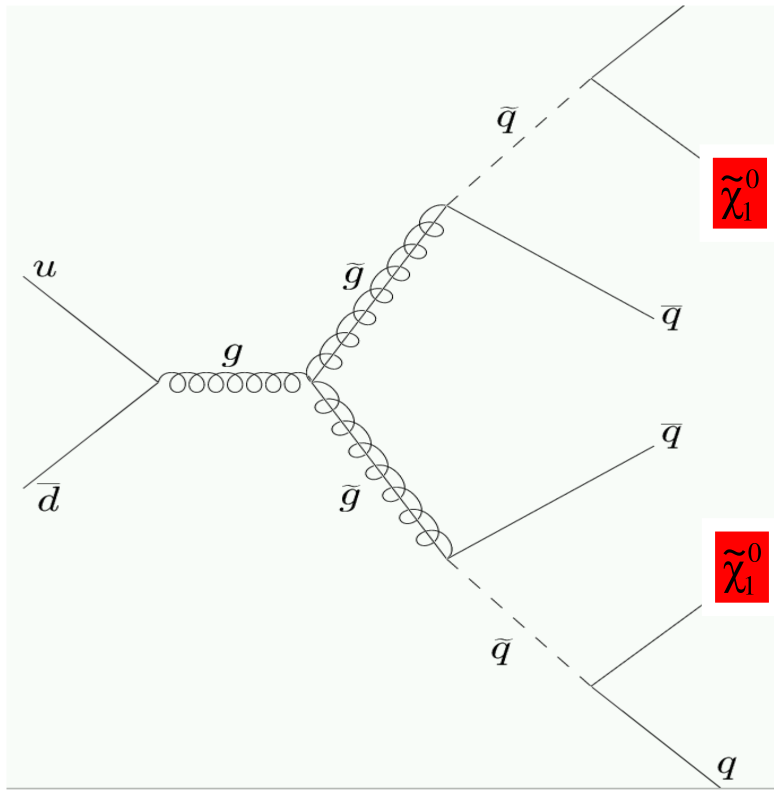
Supersymmetry at colliders

Gluino production and decay: Missing Energy Signature

Supersymmetric Particles tend to be heavier if they carry color charges.

Particles with large Yukawas tend to be lighter.

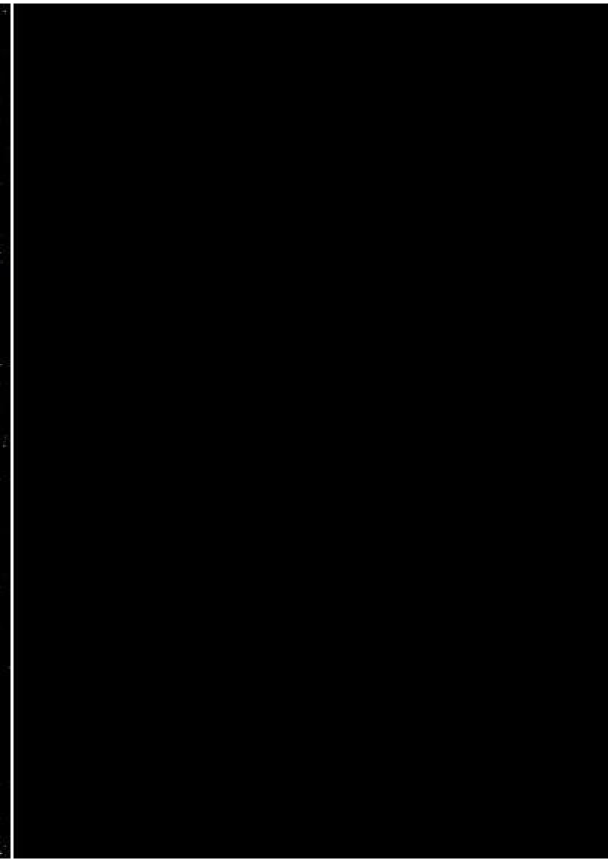
Charge-less particles tend to be the lightest ones.



➢ **Lightest supersymmetric particle = Excellent Cold dark matter candidate.**

What is the Dark Matter ?

Luminous Matter

Luminous Matter

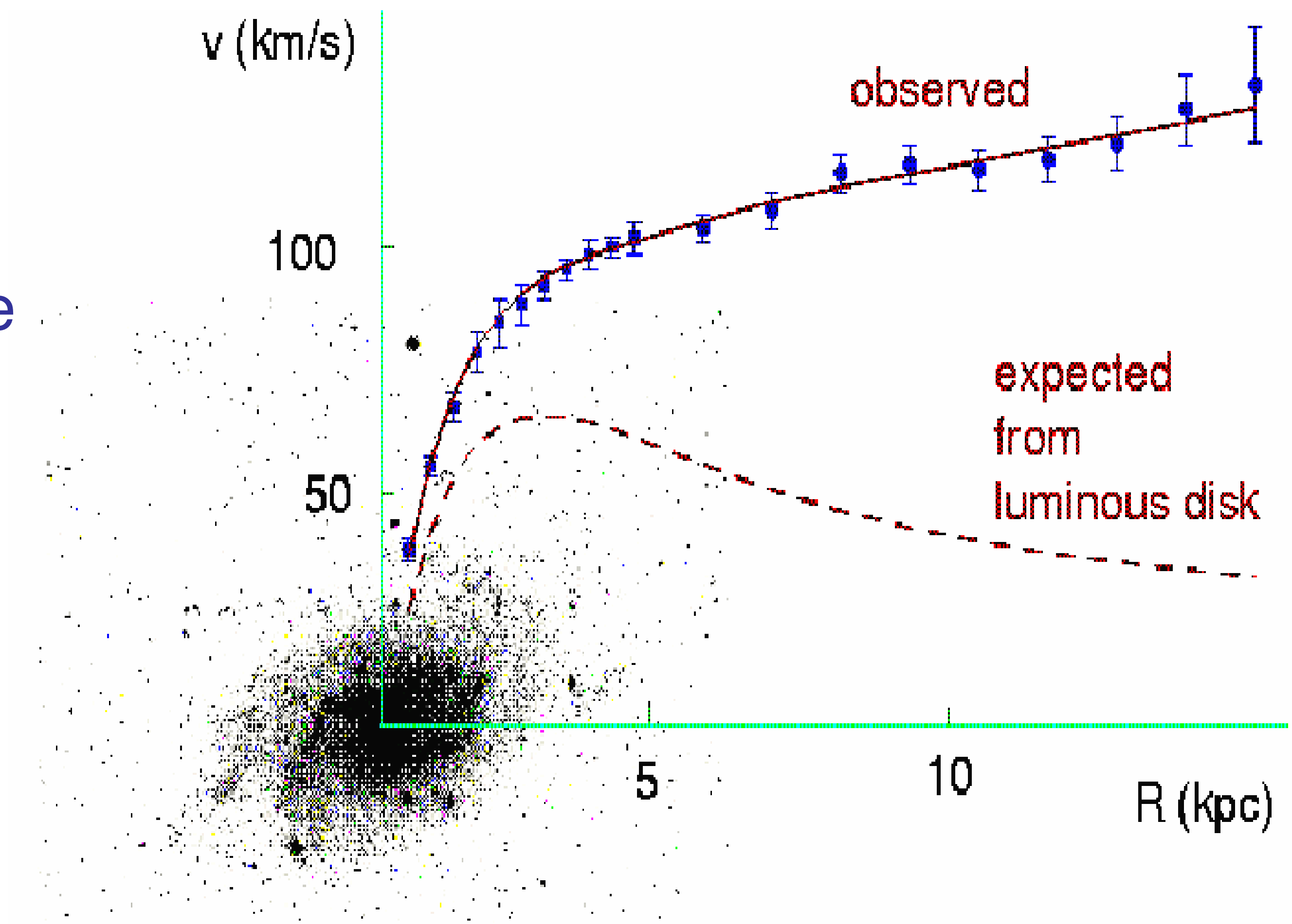
Dark Matter

Evidence for Dark Matter:

Rotation velocity of stars far from galactic center . Gravity prediction:

$$\frac{v^2}{r} = G_N \frac{M(r)}{r^2} \quad \Rightarrow \quad v^2 \propto \frac{1}{r}$$

Strong evidence for additional, non-visible source of matter



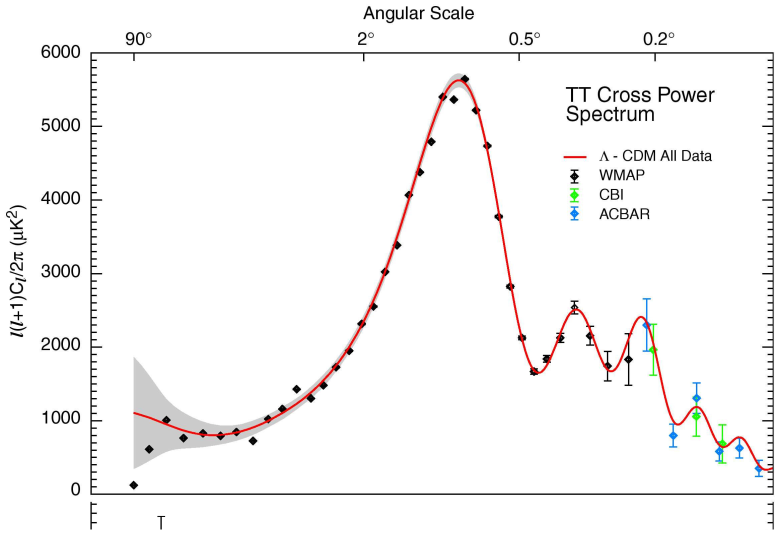
Cosmic Microwave Background
WMAP

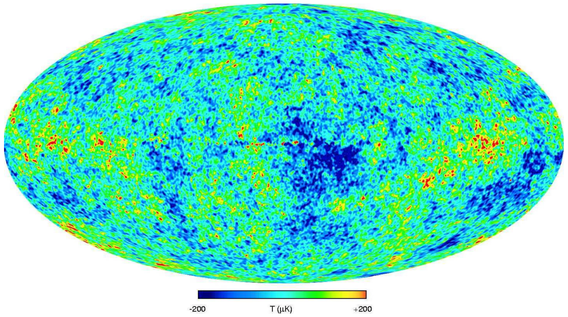
h=0.71±0.04

$\Omega_M h^2$=0.135±0.009

$\Omega_B h^2$=0.0224±0.0009

Ω_{tot}=1.02±0.02





Baryon Abundance

- Information on the baryon abundance comes from two main sources:
- Abundance of primordial elements. When combined with Big Bang Nucleosynthesis tell us

$$\eta = \frac{n_B}{n_\gamma} \quad , \qquad n_\gamma = \frac{421}{\mathrm{cm}^3}$$

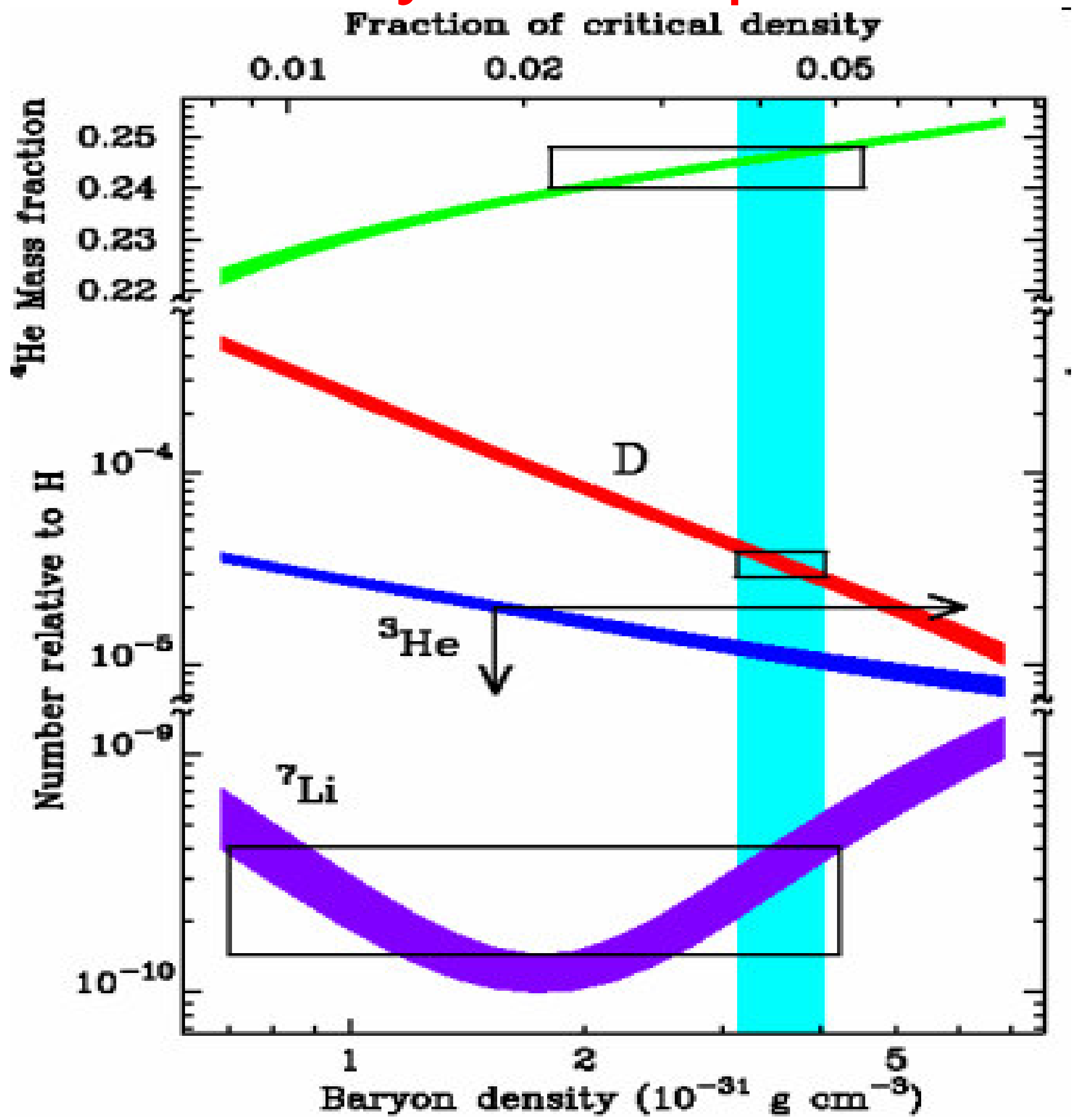
- CMBR, tell us ratio

$$\frac{\rho_B}{\rho_c} \equiv \Omega_B, \qquad \rho_c \approx 10^{-5} h^2 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

- There is a simple relation between these two quantities

$$\eta = 2.68\ 10^{-8} \Omega_B h^2$$

Element Abundance and Big-Bang Nucleosynthesis predictions



$1\,\mathrm{GeV} \approx 1.6\ 10^{-24}\ \mathrm{g}$

Possible Origin of Dark Matter

- Most likely origin of dark matter is associated with Weakly Interacting Massive Particles

- The lightest neutral particle in supersymmetric theories provides a natural candidate.

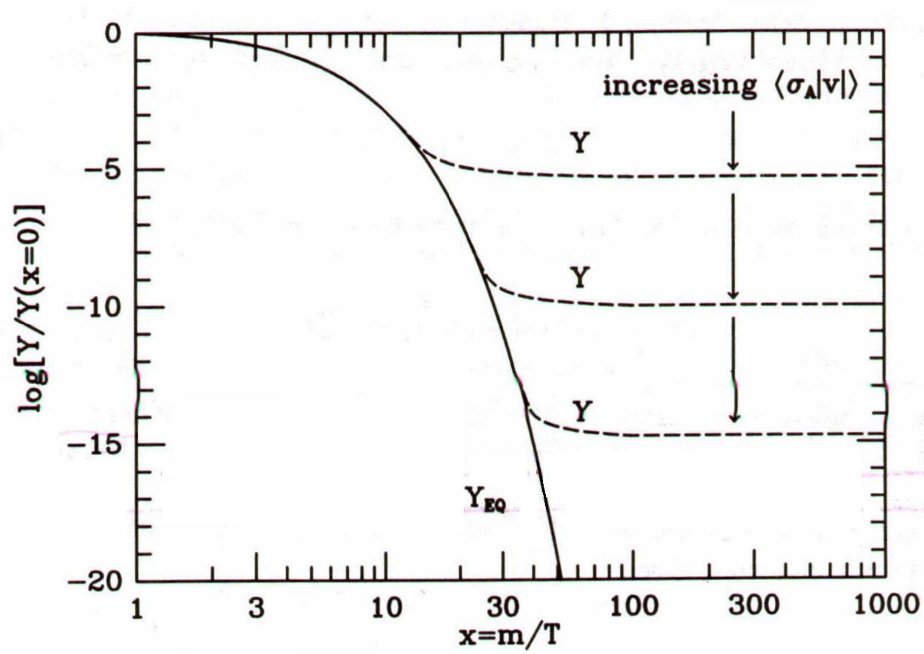
Evolution of Dark Matter Density

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\mathrm{eff}} v \rangle (n^2 - n_{eq}^2), \qquad n_{eq} \approx \exp(-m/T)$$

$\langle \sigma_{\mathrm{eff}} v \rangle$ Thermal average of (co-)annihilation cross section

$$Y = \frac{n}{s}$$

$$s \approx g_* T^3$$



Weak-scale size cross sections and masses give the right dark-matter density

Parameter in Minimal Supersymmetric Models

- In models of supersymmetry, masses depend on supersymmetry breaking parameters.

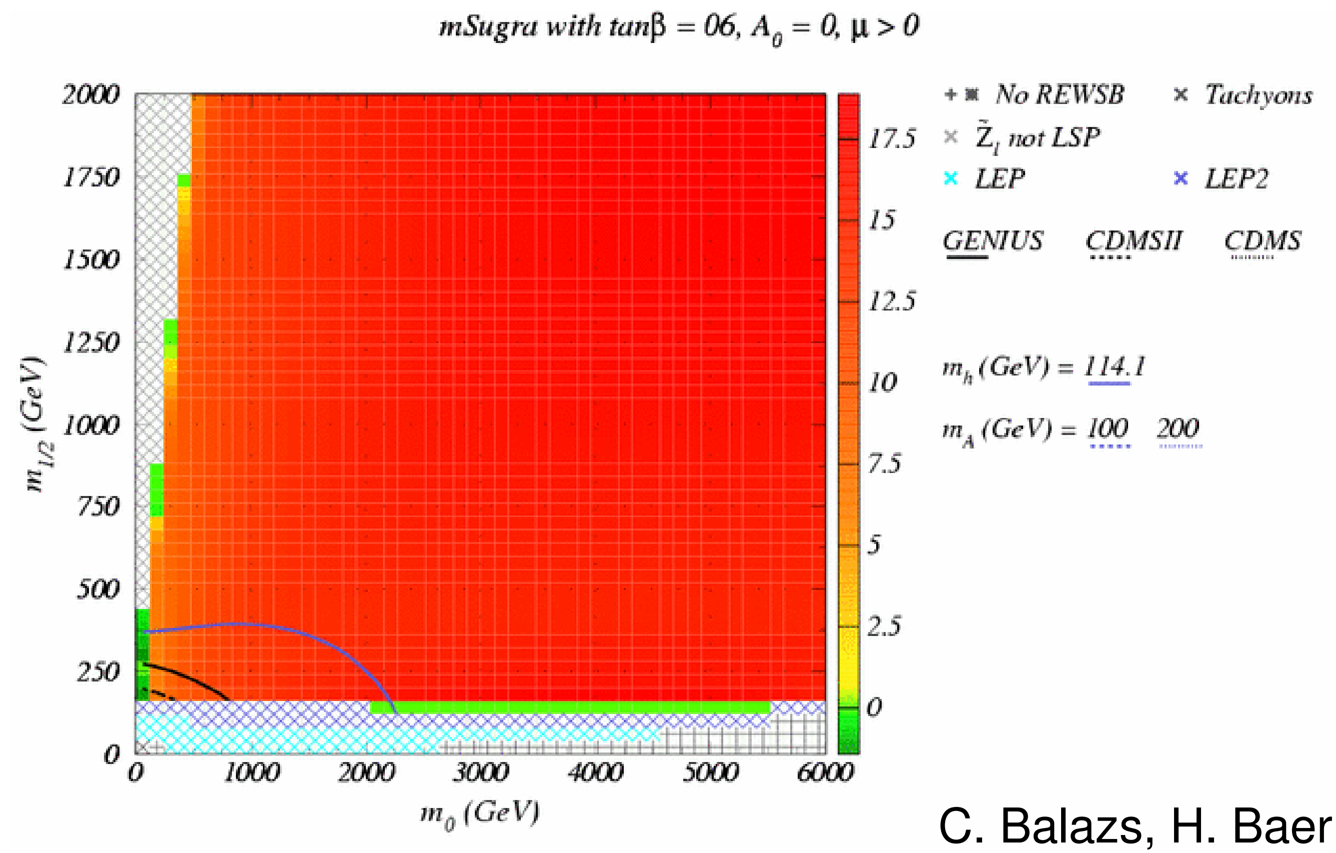
- Starting with similar masses for all scalar particles at small distance, m_0 ,observable masses differ significantly.

  Masses affected by quantum corrections, which also depend on the value of the gaugino masses at high energies, $m_{1/2}$.

  Finally, there are two Higgs doublets in supersymmetric models, and spectrum depends on the ratio of there vacuum expectation value,

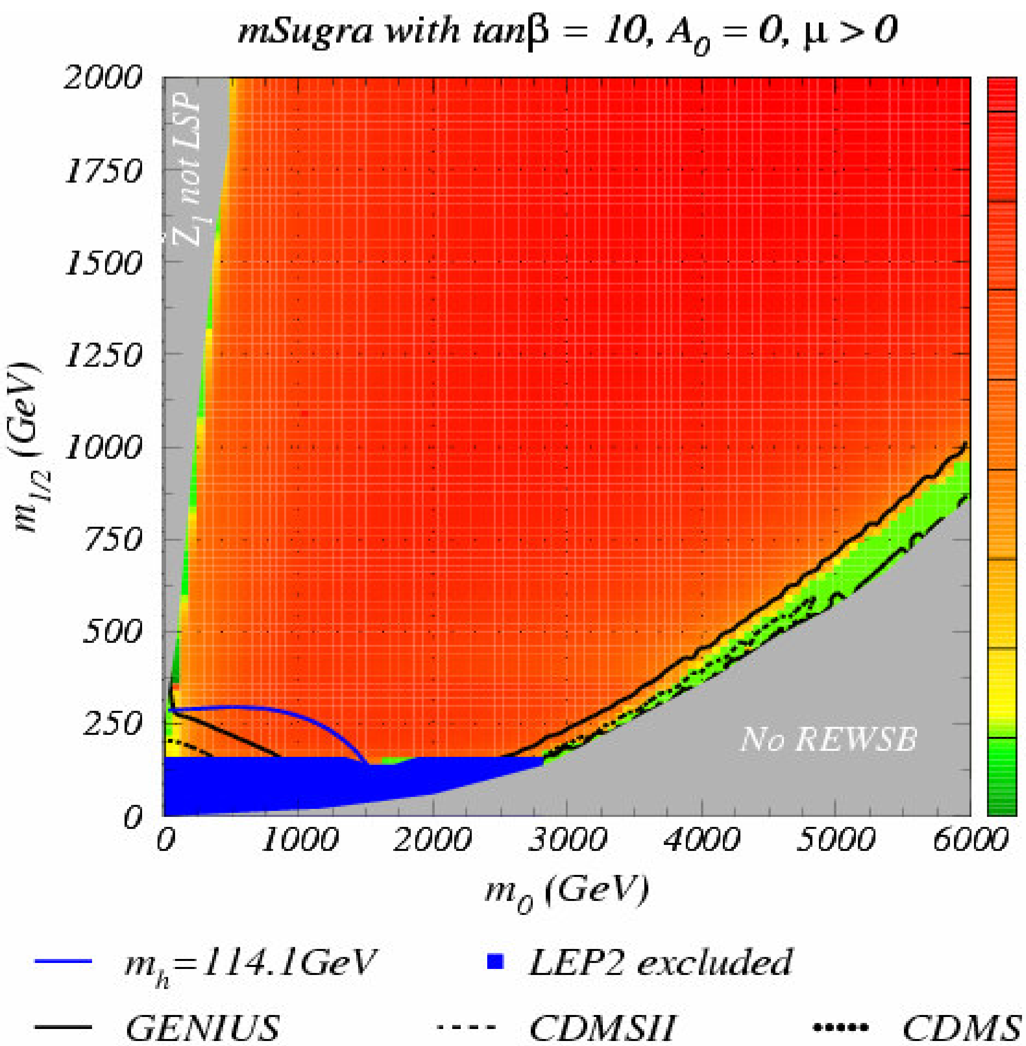
$$\tan\beta = \frac{v_1}{v_2}$$

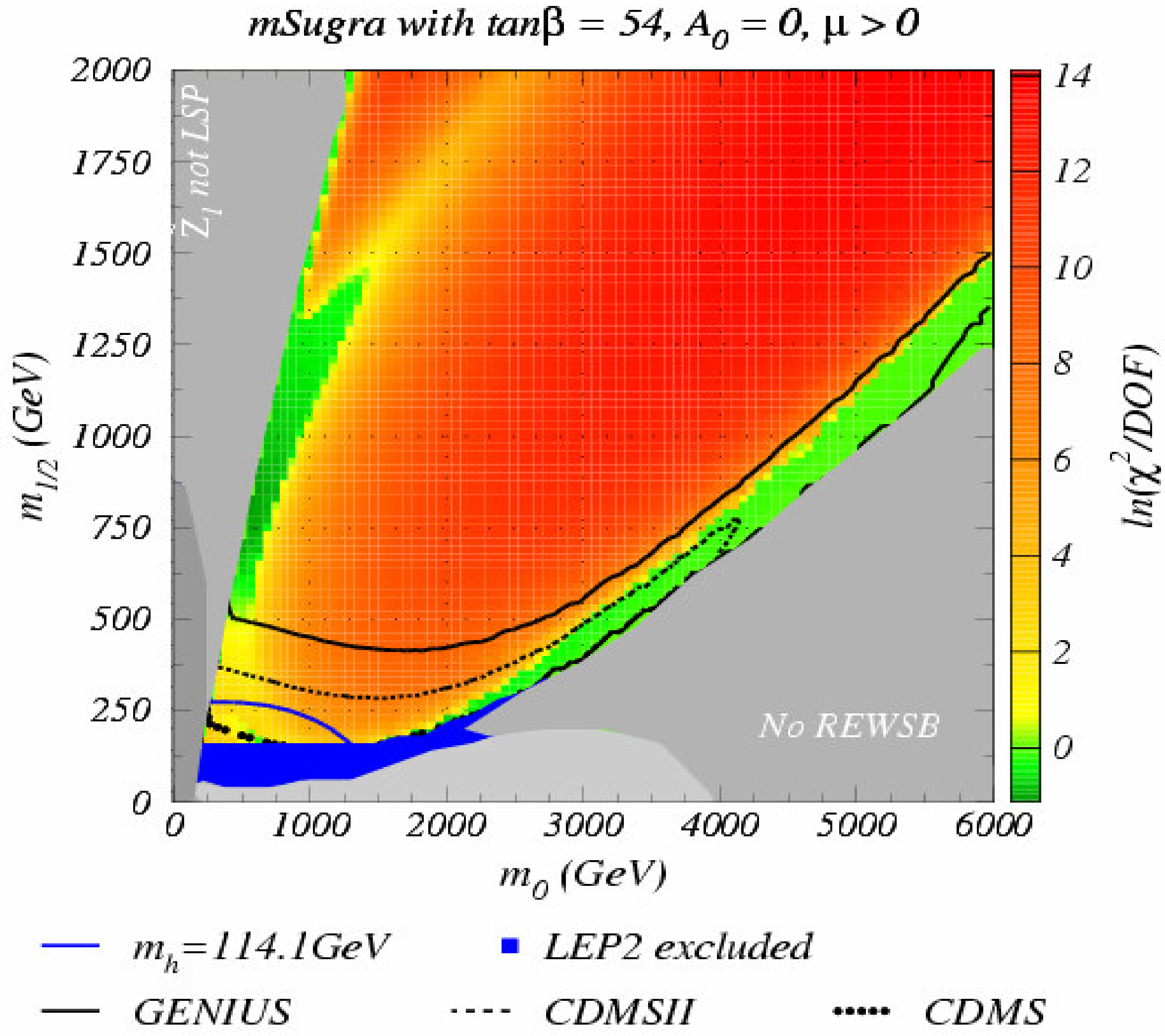
Regions of parameter space consistent with Dark Matter Density and Experimental Constraints



C. Balazs, H. Baer '03

Green areas allowed by all constraints


mSugra with tanβ = 10, A0 = 0, μ > 0
Z1 not LSP
No REWSB
m1/2 (GeV)
m0 (GeV)
ln(χ2/DOF)
mh=114.1GeV
LEP2 excluded
GENIUS
CDMSII
CDMS



mSugra with tanβ = 54, A_0 = 0, μ > 0
$\tilde{Z}_1$ not LSP
No REWSB
$m_{1/2}$ (GeV)
m_0 (GeV)
ln(χ^2/DOF)
2000
1750
1500
1250
1000
750
500
250
0
1000
2000
3000
4000
5000
6000
14
12
10
8
6
4
2
0
m_h=114.1GeV
LEP2 excluded
GENIUS
CDMSII
CDMS

Origin of the Baryon Asymmetry

The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as matter.
- Observable Universe is composed of matter.
- Anti-matter is only seen in cosmic rays and particle physics accelerators
- The rate observed in cosmic rays consistent with secondary emission of antiprotons

$$\frac{n_{\bar{P}}}{n_{P}} \approx 10^{-4}$$

Baryon-Antibaryon asymmetry

- Baryon Number abundance is only a tiny fraction of other relativistic species

$$\frac{n_B}{n_\gamma} \approx 6\ 10^{-10}$$

- But in early universe baryons, antibaryons and photons were equally abundant. What explains the above ratio ?

- Explanation: Baryons and Antibaryons annihilated very efficiently. No net baryon number if B would be conserved at all times.

- What generated the small observed baryon-antibaryon asymmetry ?

Generation of Baryon Asymmetry

Three conditions, first defined by Sakharov

- Non-conservation of Baryon Number
- C and CP Violation (Violation of symmetry of interactions under interchange of particle by antiparticles)

Otherwise, number of baryons would equal number of antibaryons

- Non-equilibrium processes (Rate of increase of B larger than the one of decrease of B)

All three requirements fulfilled in the SM.

Electroweak Baryogenesis

Baryogenesis at low Energies

(Kuzmin, Rubakov, Shaposhnikov)

- Idea : Baryon Number not generated at high energies, can be generated at the electroweak phase transition

Electroweak Baryogenesis

- Start with B=L=0
- First-order phase transition . Rate suppressed in the broken phase: Non-equilibrium

$$\Gamma(\Delta\mathrm{B}\neq 0) \propto \mathrm{A\,T} \exp\left(-\frac{\mathrm{E_{sph}}}{\mathrm{T}}\right) \qquad E_{sph} = \frac{8\pi\, \mathrm{v}(\mathrm{T})}{g_W}$$

- Creation of Baryon Number from CP violating sources

Electroweak Baryogenesis in the Standard Model

- SM fufills the Sakharov conditions:
- Baryon number violation: Anomalous Processes
- CP violation: Quark CKM mixing
- Non-equilibrium: Possible at the electroweak phase transition.

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(-\frac{10^{16}}{\mathrm{T_c(GeV)}} \exp\left(-\frac{\mathrm{E_{sph}}(\mathrm{T_c})}{\mathrm{T_c}} \right) \right)$$

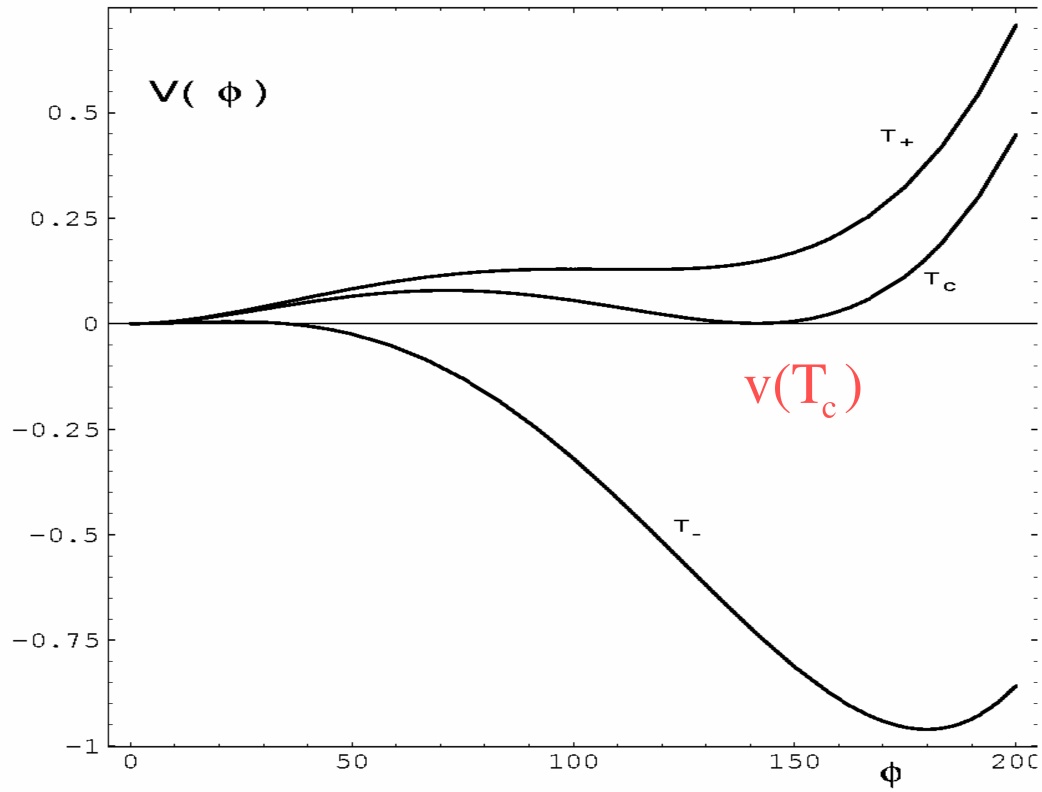
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

Therefore, to preserve the baryon asymmetry

$$\frac{\mathrm{v}(T_c)}{T_c} > 1$$

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order Phase Transition



Finite Temperature Higgs Potential

$$V = D(T^2 - T_0^2)H^2 + ET\ H^3 + \lambda\ H^4$$

While D receives contributions at one-loop proportional to the sum of the couplings of all bosons and fermions squared, and is responsible for the phenomenon of symmetry restoration

E receives contributions proportional to the sum of the cube of all light boson particle couplings

$$\frac{\mathrm{v}(\mathrm{T_c})}{\mathrm{T_c}} \approx \frac{\mathrm{E}}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{\mathrm{m_H^2}}{\mathrm{v}^2}$$

Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass,

$$\frac{\mathrm{v}(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H \quad < 40\ \text{GeV}.$$

Electroweak Baryogenesis in the SM is ruled out

Supersymmetry provides the necessary ingredients for the realization of the Electroweak Baryogenesis scenario !

Preservation of the Baryon Asymmetry

- EW Baryogenesis requires new boson degrees of freedom with strong couplings to the Higgs.

- Supersymmetry provides a natural framework for this scenario.

- Relevant SUSY particle: Superpartner of the top.

- Each stop has six degrees of freedom (3 of color, two of charge) and coupling of order one to the Higgs

$$E_{SUSY} = \frac{g_w^3}{4\pi} + \frac{h_t^3}{2\pi} \approx 8\, E_{SM}$$

- Since $\dfrac{v(T_c)}{T_c} \approx \dfrac{E}{\lambda}$, with $\lambda \propto \dfrac{m_H^2}{v^2}$

Higgs masses up to 120 GeV may be accomodated

Constraints on the Stop Sector

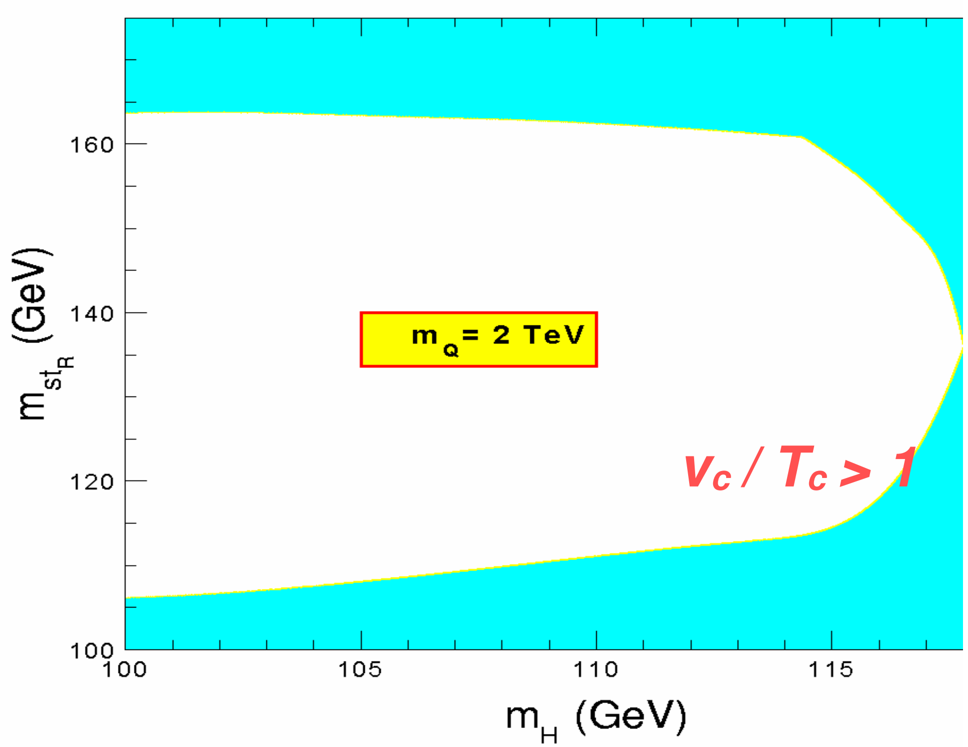
- The top quark has two supersymmetric partners, one for each chirality (left and right).

- One of the stops has to be light, in order to make the phase transitioin strongly first order

- Second stop needs to be heavier than about 1 TeV in order to make the Higgs mass larger than the current bound, of about 114 GeV.

- Upper bound on the Higgs imposed by the requirement of the preservation of the baryon asymmetry.

Limits on the Stop and Higgs Masses to preserve the baryon asymetry



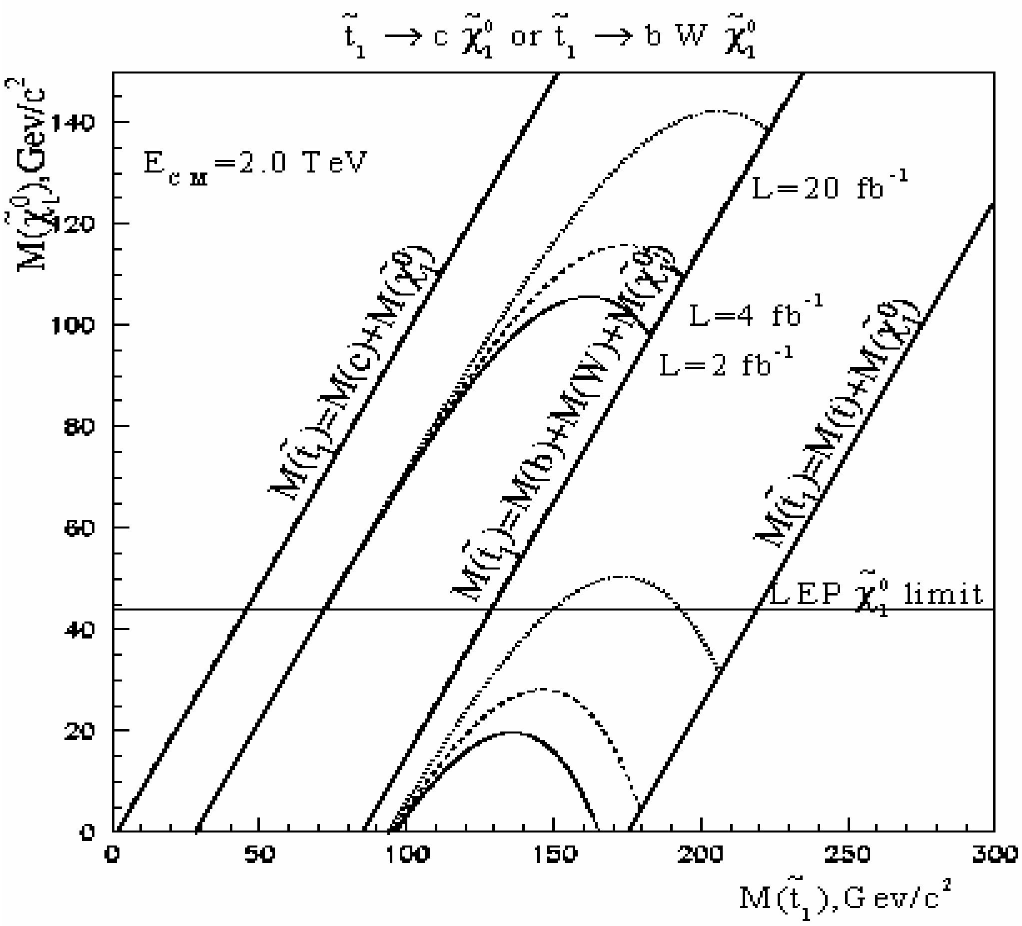
Higgs masses smaller than 120 GeV and a stop masses below the top quark mass required

M.Carena, M. Quiros, C.W.' 98

Stop Signatures

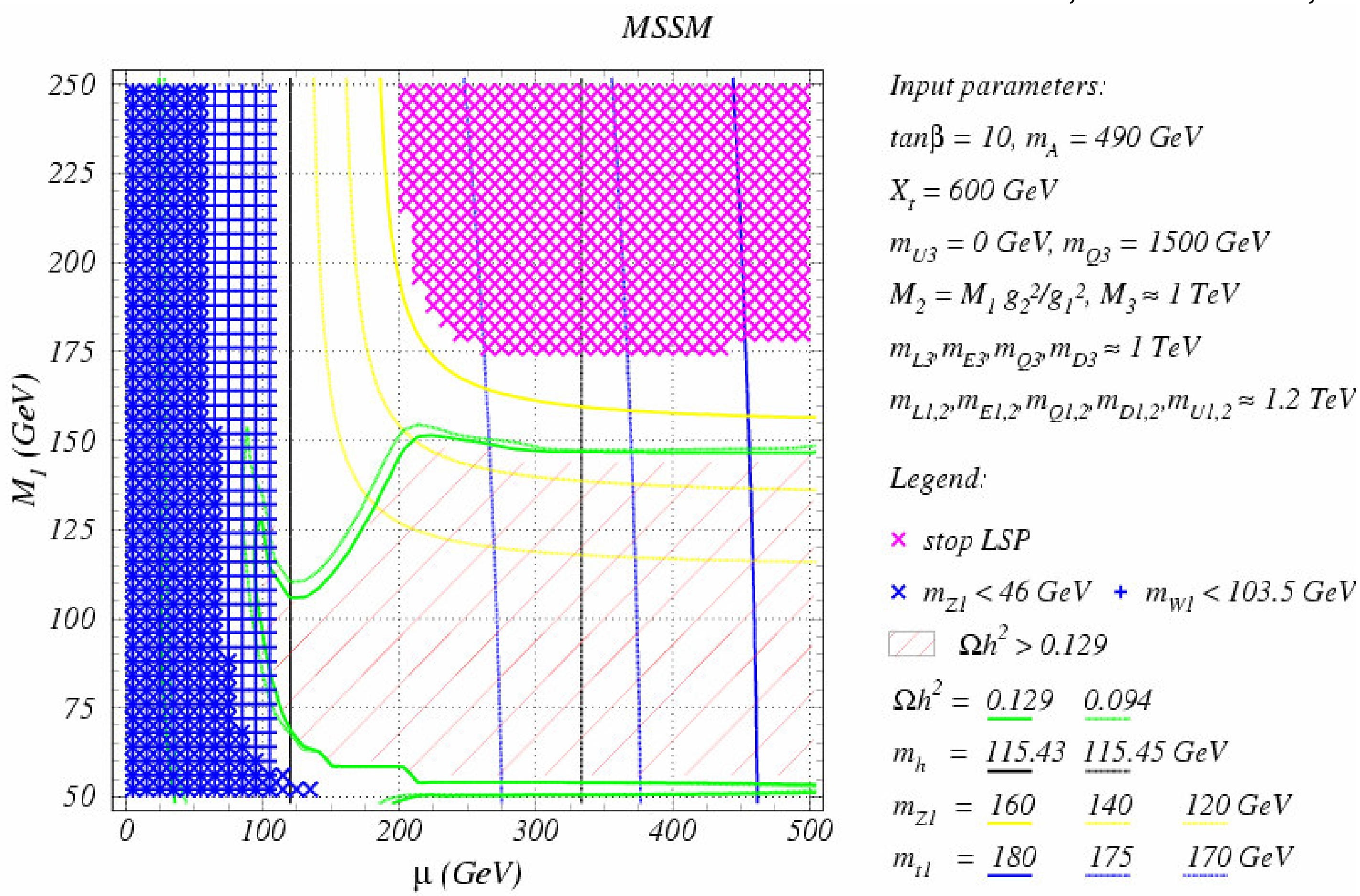
- Light Stop can decay into the lighter charginos or neutralinos.
- Stop signatures depend on this and also on the mechanism of supersymmetry breaking.
- In standard scenarios, where neutralino is the dark matter, stop may decay into a light up-quark and a neutralino: Two jets and missing energy.
- In models in which supersymmetry is broken at low energies, the neutralino may decay into a photon and a gravitino, the superpartner of the graviton.

Stop Signatures at the Tevatron
Neutralino as Dark Matter



Dark Matter and Electroweak Baryogenesis in the MSSM

C. Balazs, M. Carena, C.W. '04



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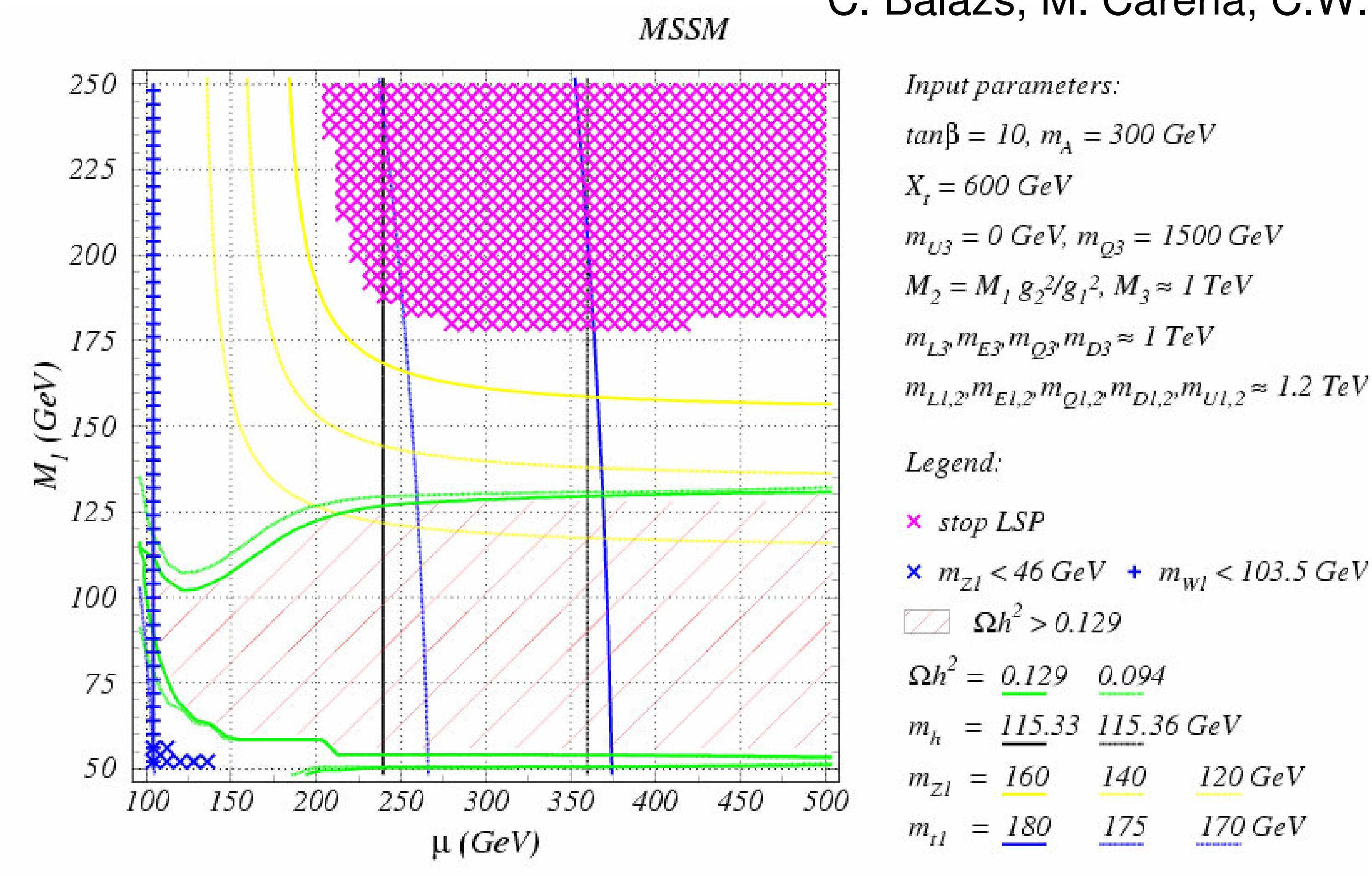

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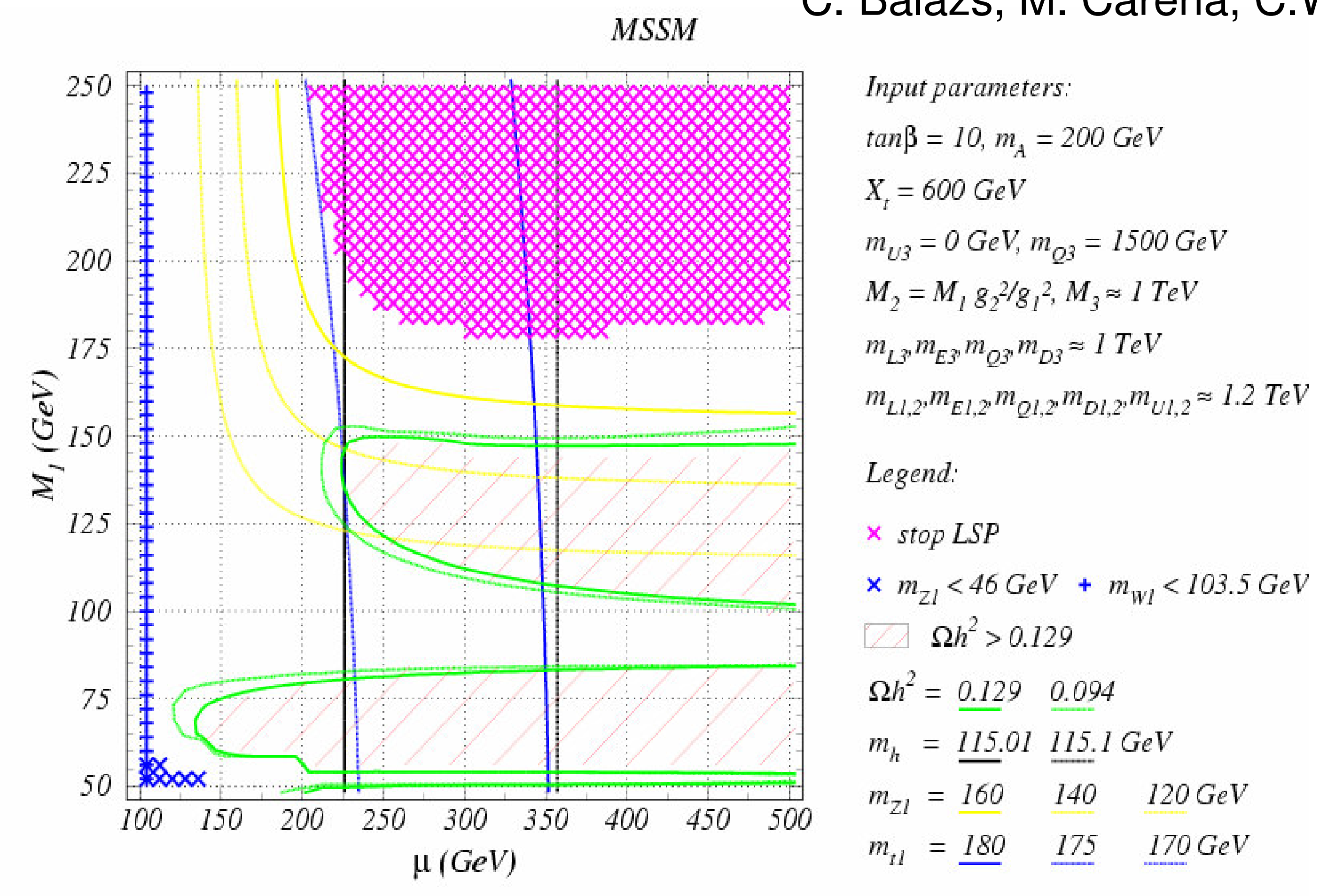

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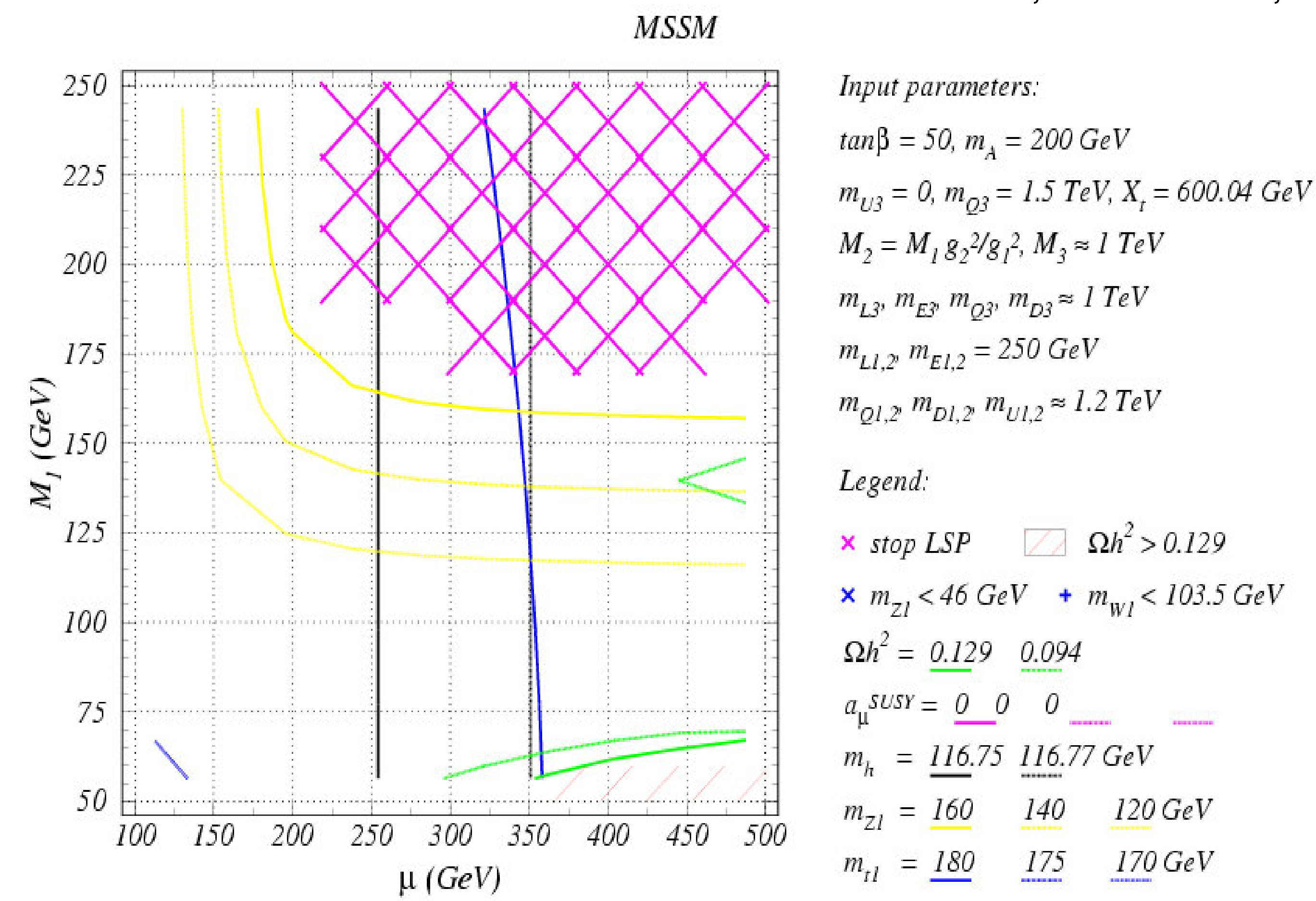
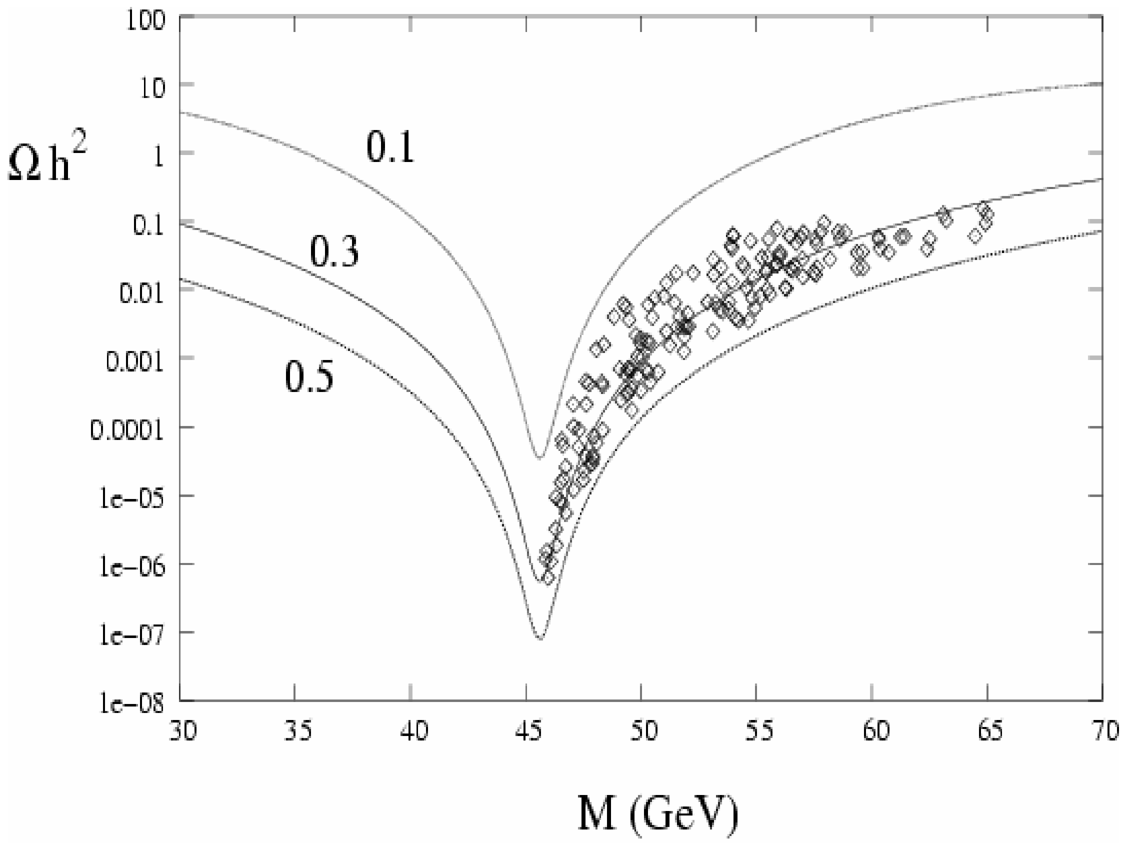


Going Beyond the MSSM

- Minimal Supersymmetric scenario highly constrained.
- Dark Matter and Baryogenesis come from different sources.
- With D. Morrissey and A. Menon we are investigating a minimal extension of the MSSM: Addition of a singlet field.
- Dark Matter and Electroweak Baryogenesis have common origins in this model.

Relic Density as a function of neutralino mass

A.Menon, D. Morrissey,C.W. '04



Diamonds consistent with all experimental constraints and with v(T)/T > 1.

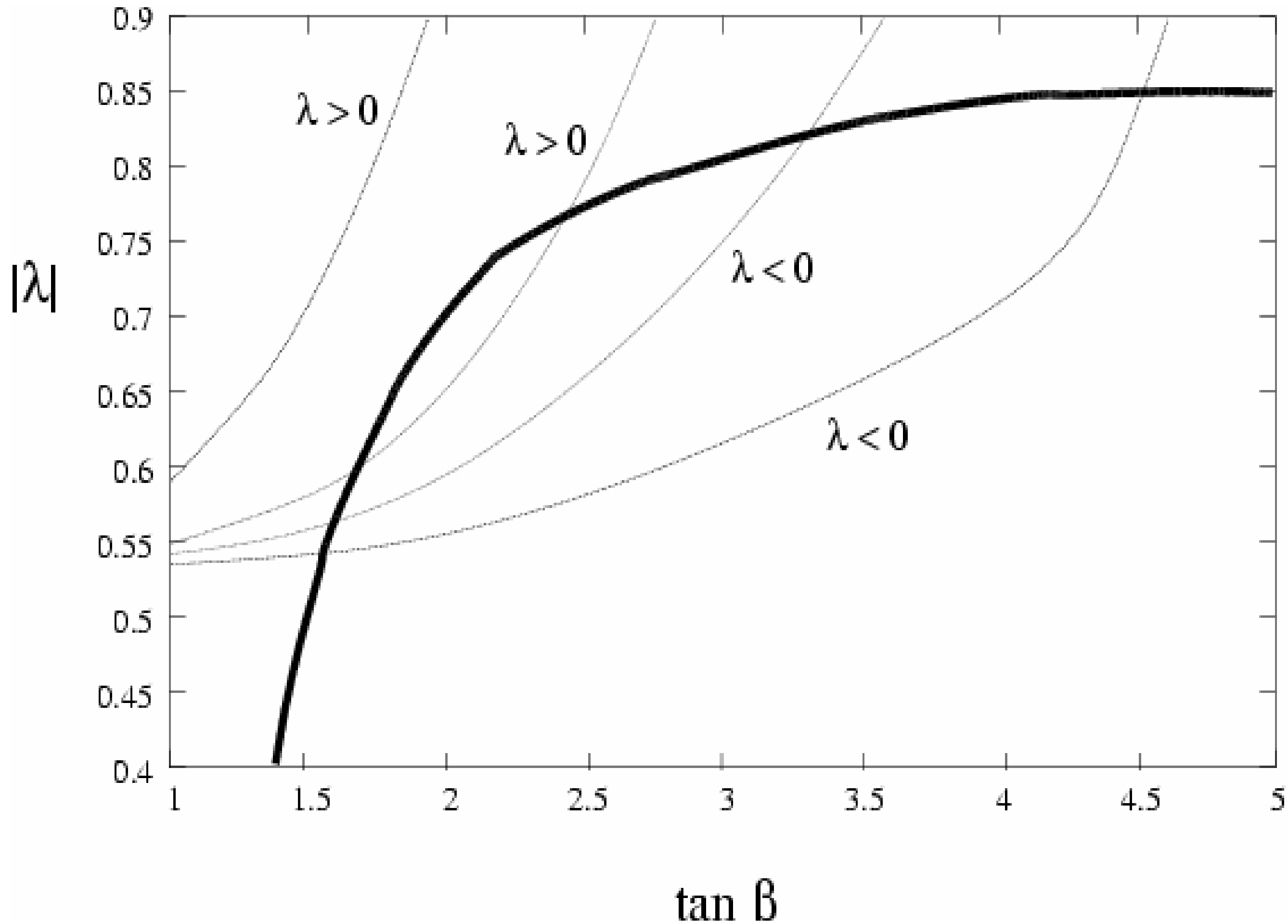
Conclusions

- Supersymmetry provides an extension of the SM with many phenomenologically attractive features

- It leads to a natural candidate for the origin of the dark matter density

- Most surprisingly, it may also be helpful in understanding the matter-antimatter asymmetry.

Other Issues



0.9
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0.5
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λ > 0
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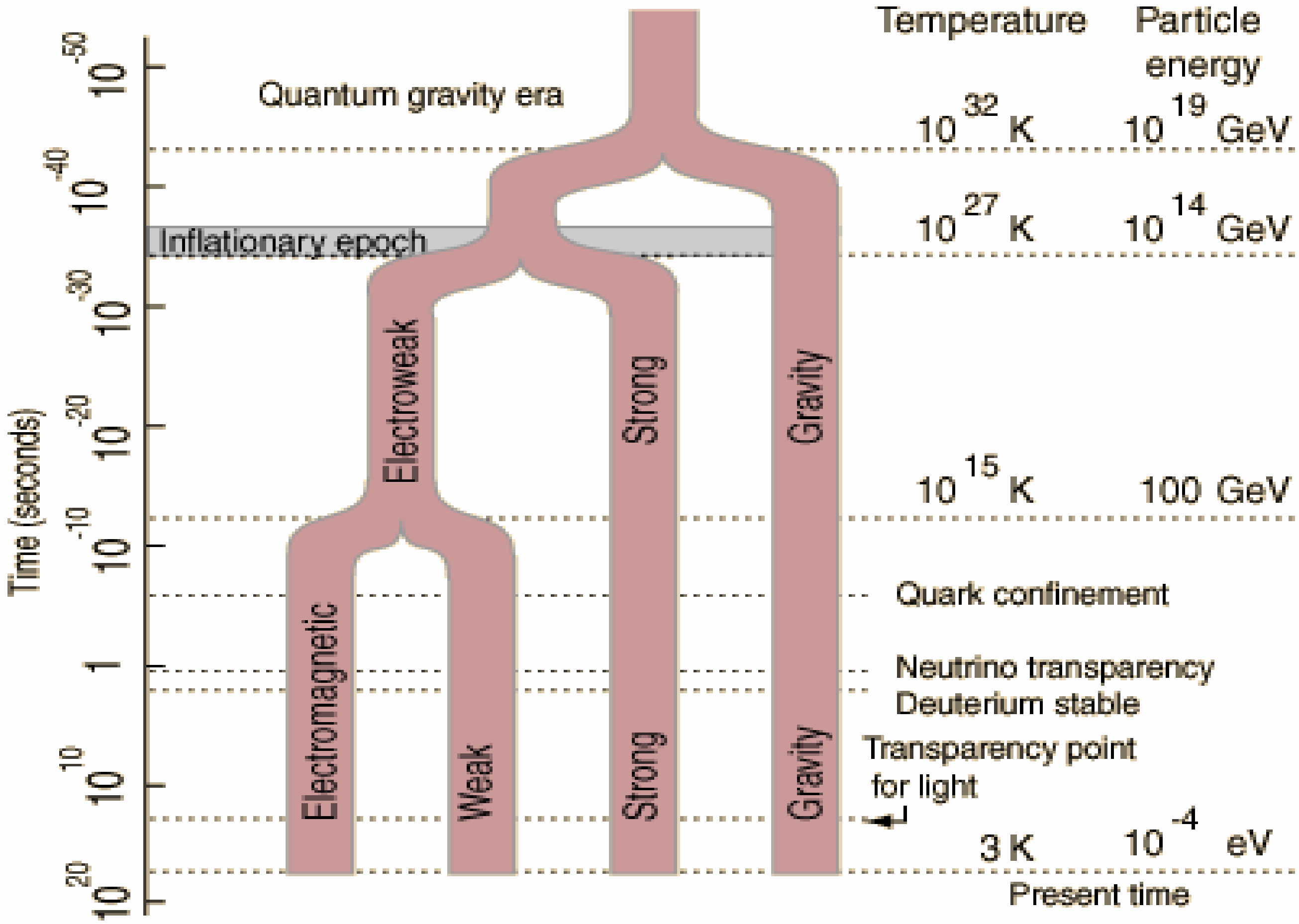
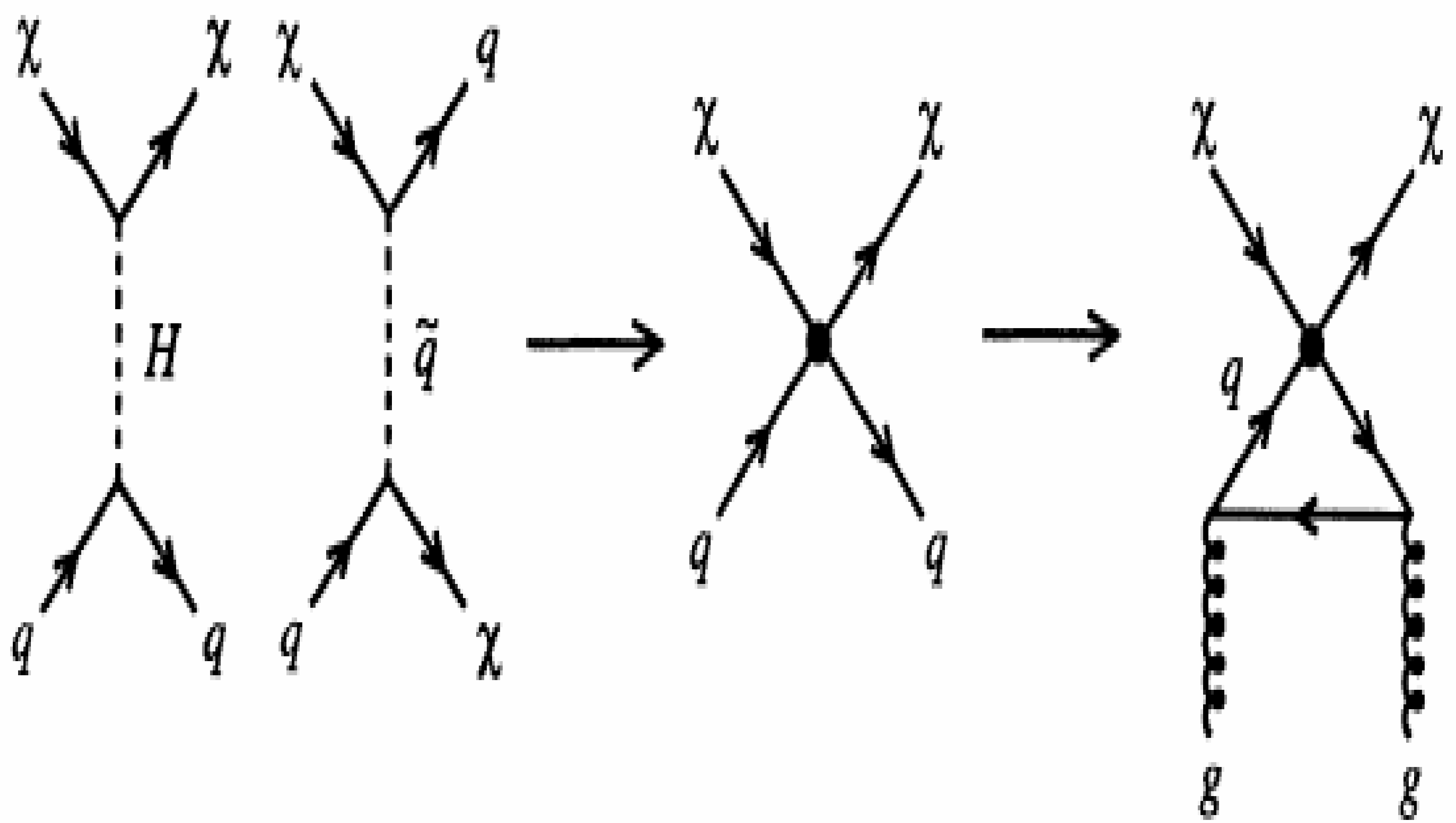


Temperature
Particle energy
Quantum gravity era
10^32 K
10^19 GeV
10^27 K
10^14 GeV
Inflationary epoch
Electroweak
Strong
Gravity
10^15 K
100 GeV
Quark confinement
Neutrino transparency
Deuterium stable
Transparency point for light
Electromagnetic
Weak
3 K
10^-4 eV
Present time
Time (seconds)
10^-50
10^-40
10^-30
10^-20
10^-10
1
10^10
10^20



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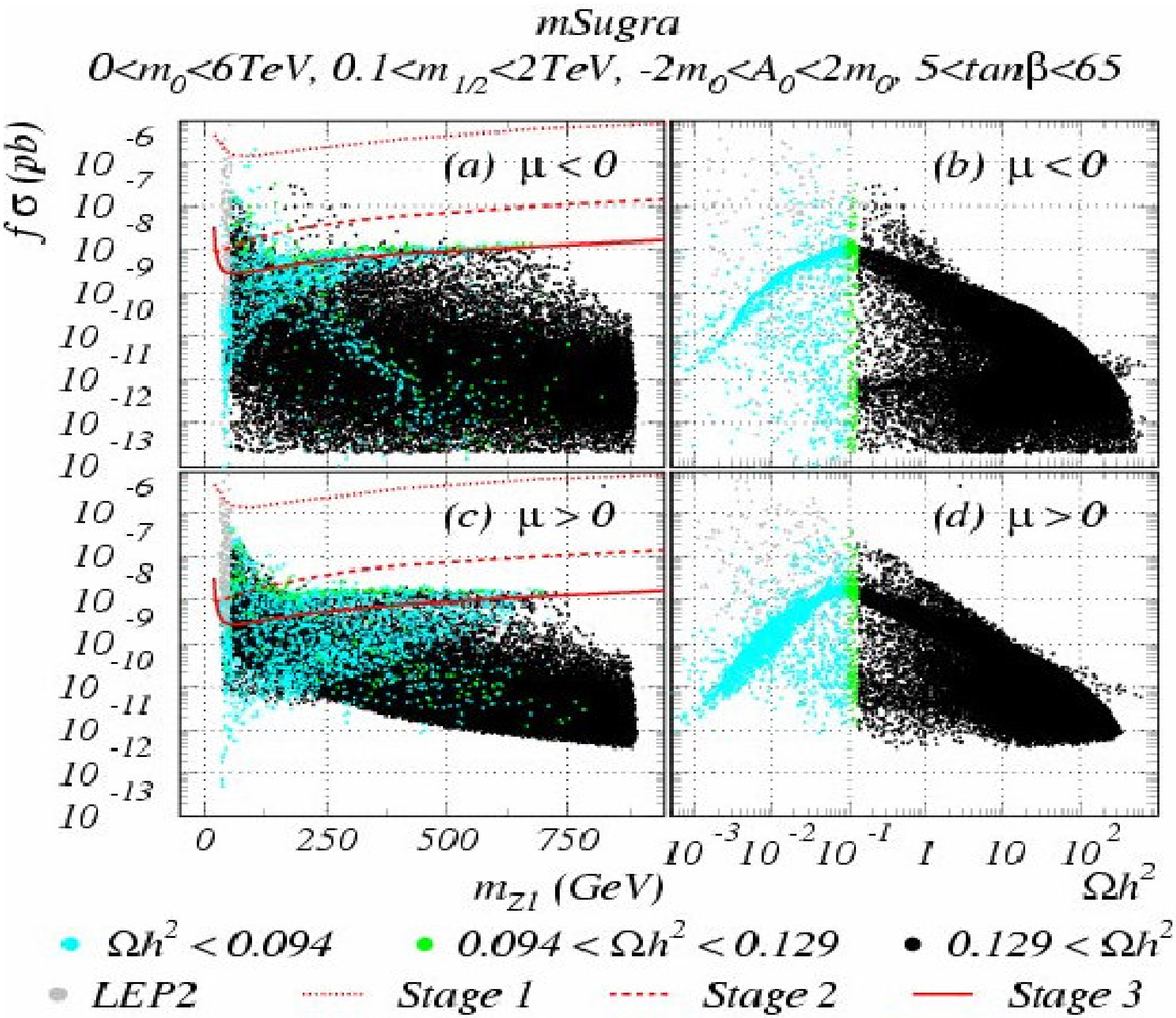
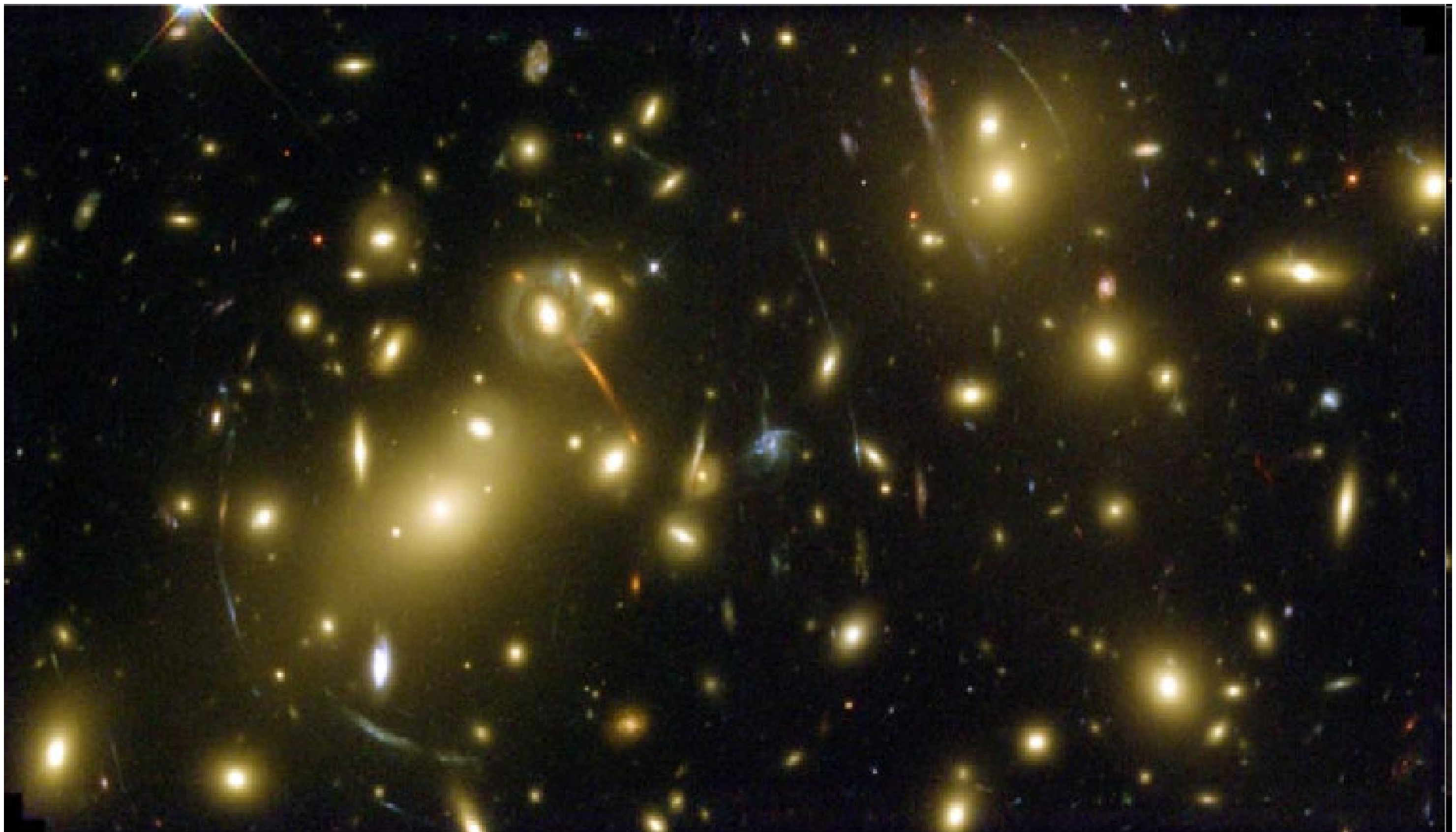
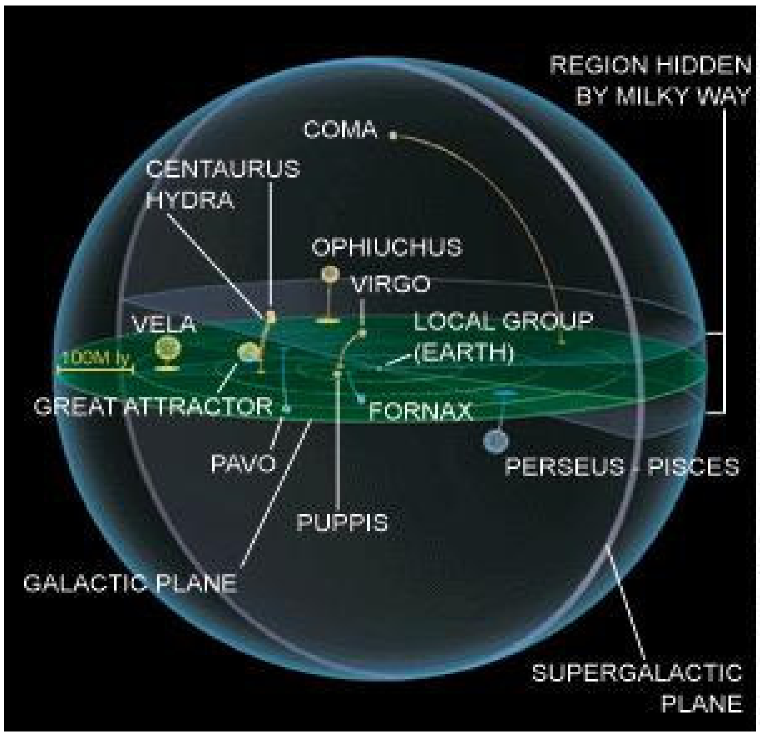

mSugra
0<m_0<6TeV, 0.1<m_1/2<2TeV, -2m_0<A_0<2m_0, 5<tanβ<65
fσ (pb)
(a) μ < 0
(b) μ < 0
(c) μ > 0
(d) μ > 0
m_Z1 (GeV)
Ωh^2
Ωh^2 < 0.094
0.094 < Ωh^2 < 0.129
0.129 < Ωh^2
LEP2
Stage 1
Stage 2
Stage 3



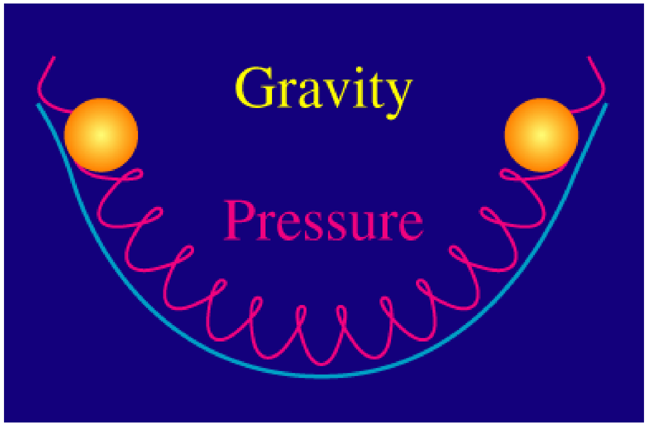
Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08


REGION HIDDEN
BY MILKY WAY
COMA
CENTAURUS
HYDRA
OPHIUCHUS
VIRGO
VELA
LOCAL GROUP
(EARTH)
100M ly
GREAT ATTRACTOR
FORNAX
PAVO
PERSEUS - PISCES
PUPPIS
GALACTIC PLANE
SUPERGALACTIC
PLANE

CMB as a sound wave

(Animation by W. Hu)



Last scattering surface : snapshot of the photon-baryon fluid

- Acoustic structures in spherical harmonics

On large scales : primordial ripples, purely GR Effects

Forced damped harmonic oscillator

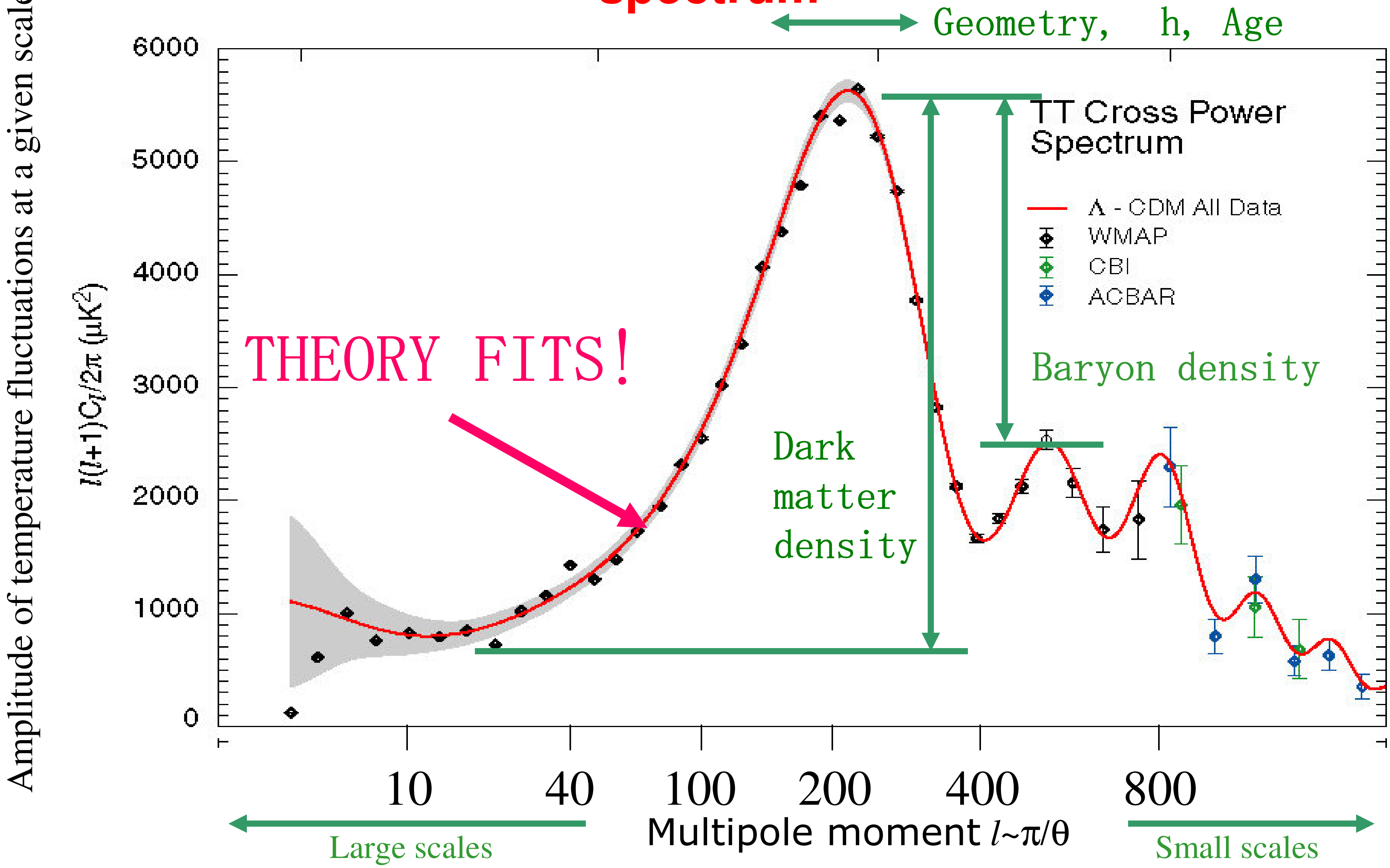
On smaller scales: { Photons radiation pressure, Gravity compression } Sound waves

Stop oscillating at recombination

Smaller than photon mean free path: Exponentially damped by photon diffusion

Horizon size at LSS → Fundamental mode

Sound wave on the sky: WMAP temperature power spectrum



After February 11, 2003